LLNL-PROC-660129

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A. Link, C. Halvorson, E. C. Hagen, D. V. Rose, D. R. Welch , A. Schmidt

September 12, 2014

9th International Dense Z Pinch Conference
Napa, CA, United States
August 3, 2014 through August 7, 2014

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Particle-In-Cell Modeling For MJ Scale Dense Plasma Focus With Varied Anode Shape

A. Link[1a], C. Halvorson[1], E. C. Hagen[2], D. V. Rose[3], D. R. Welch[3], A. Schmidt[1]

[1]Lawrence Livermore National Laboratory, Livermore, CA 94550
[2] National Security Technologies Las Vegas, NV 89030
[3] Voss Scientific LLC Albuquerque NM 87108
[a)]link6@llnl.gov

Abstract. Megajoule scale dense plasma focus (DPF) Z-pinches with deuterium gas fill are compact devices capable of producing 10^12 neutrons per shot but past predictive models of large-scale DPF have not included kinetic effects such as ion beam formation or anomalous resistivity. We report on progress of developing a predictive DPF model by extending our 2D axisymmetric collisional kinetic particle-in-cell (PIC) simulations[1] from the 4 kJ, 200 kA LLNL DPF[2] to 1 MJ, 2 MA Gemini DPF using the PIC code LSP[3]. These new simulations incorporate electrodes, an external pulsed-power driver circuit, and model the plasma from insulator lift-off through the pinch phase. To accommodate the vast range of relevant spatial and temporal scales involved in the Gemini DPF within the available computational resources, the simulations were performed using a new hybrid fluid-to-kinetic model. This new approach allows single simulations to begin in an electron/ion fluid mode from insulator lift-off through the 5-6 μs run-down of the 50+ cm anode, then transition to a fully kinetic PIC description during the run-in phase, when the current sheath is 2-3 mm from the central axis of the anode. Simulations are advanced through the final pinch phase using an adaptive variable time-step to capture the fs and sub-mm scales of the kinetic instabilities involved in the ion beam formation and neutron production. Validation assessments are being performed using a variety of different anode shapes, comparing against experimental measurements of neutron yield, neutron anisotropy and ion beam production.

INTRODUCTION

We describe here a series of preliminary simulations of the anode shape's influence on neutron yield from a megajoule-scale dense plasma focus device (DPF). A DPF is a compact, simple device consisting of two coaxial electrodes with a pulsed high-voltage source at one end (Figure 1) and filled with a low-density gas. The application of high-voltage across the electrodes induces a flashover event along the surface of the insulator and a forms a conducting plasma sheath. The is plasma sheath is accelerated by J x B interaction with the current flowing from the pulsed power down the electrode, accreting and ionizing the neutral gas along its path and is often referred to as the "Run-Down" phase of a DPF. When the plasma reaches the end of the anode, the plasma is accelerated radially inward or "Runs In" and forms a dense "pinched" plasma column on axis. During this pinch phase of the evolution, the plasma emits a high-energy ion beam, which in the presence of Deuterium or Tritium produces fusion neutrons. The influence of the shape of the anode on pinch phase has been studied experimentally [5-6] but difficulties in full kinetic modeling of the ion-beam production in simulations as been limited until recently [1].

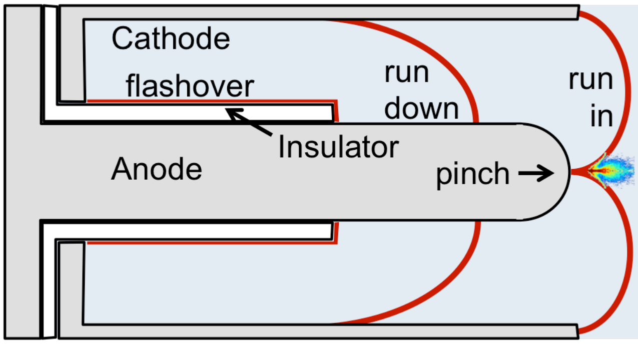

FIGURE 1 (Color Online) An illustration of the 4 phases of a Dense Plasma Focus. First the initialization of a plasma along the insulator, second plasma being accelerated to "run-down" the anode, third the radial implosion for run-in phase and finally the stagnation and formation of a pinched plasma on axis.

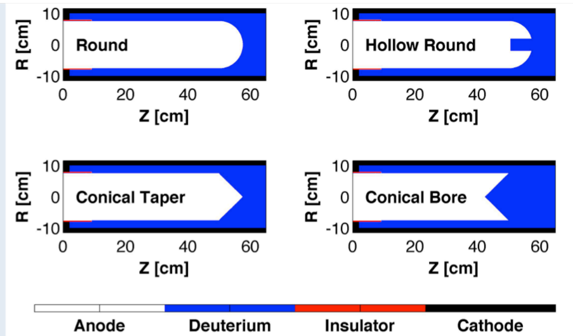

FIGURE 2 (Color Online) The four anode tip configurations. All of the shapes are identical for the first 50 cm of length with a radius of 7.6cm. A 4 mm thick insulator separates the anode from the cathode plate located near Z = 0. The Hollow Round is identical to Round anode except for a 4 cm diameter, 7.6 cm long hollow channel has been cut into the center of the anode.

SIMULATION SETUP

Simulations of the influence of the anode shape on the ion-beam were conducted using the 2D3V particle-in-cell code LSP [3] in an R-Z cylindrical geometry and four anode shapes were modeled (Figure 2): a conventional round tip anode, round tip anode with a hollow section at the center, anode with a 45^o conical tip and an anode with a 45^o conical bore all with a static fill of Deuterium. These anodes only varied in the shape of the tip of the anode, with the straight cylindrical portion of the anode kept constant to ensure all the shapes had similar times for the plasma to complete the "run-down" phase, similar inductances and would reach similar peak currents. The simulations include a full pulse power circuit modeled after the Gemini DPF to include the effects of finite driver response and energy, and begin initialized with a 1 mm thick, 2.5 eV plasma along the insulator surface with the remaining gas (n_i = 3.6x 10^{17} particles/cc) as a 0.01 eV plasma with 200 μm resolution in Z-direction and 100 μm resolution in R-direction. Since the electrode dimensions are so large (50-55 cm) and the time scale for the plasma to run-down is so long (5 μs), the simulations were run self-consistently in 2 phases. First during the run-down and during the majority of the run-in phases, the plasma was treated as a quasi-neutral conducting fluid. When the plasma sheath was within a few mm of the z-axis and the electron cyclotron period was approximately 1 ps, the fluid was transitioned to a distribution of kinetic particles and the simulation was continued as a fully kinetic simulation. At the transition time, in every cell that contained plasma, the fluid was replaced with particles proportional to local plasma density with 49 particles/cell/species for both ions and electrons at the ambient density and the distribution mapped to a drifting Maxwellian with the local cell temperature and drift velocity. During this transition, the cell averaged current densities, particle number densities, electron and ion temperatures, electromagnetic fields and the current/voltages in pulse power driver were continuous. The simulations were then advanced using the direct implicit method [6] with a variable time step which was adjusted to maintain $\omega_c \Delta t \leq 0.35$, where ω_c is the electron cyclotron period and Δt the current simulation time-step, keeping the electron motion resolved as the magnetic field increases as plasma pinches on axis. The simulation was fully collisional, and included D-D fusion process to produce neutrons. This hybrid fluid-kinetic approach allows LSP to maintain good energy conservation during the fluid phase and greatly reduces the computational cost with the fluid phase representing 99% of the simulation time but only 0.5% of the computational time.

The pulse power circuit starts with 300kJ of stored energy in the capacitors and delivers ~100kJ of energy to all 4 simulations in the fluid phase over the course of 5.1-5.6 μs, with the conical taper anode pinching first and the conventional anode taking the longest time to reach the axis. All of the simulations had similar peak currents reaching 1.45-1.6 MA.

SELECTED RESULTS FOR CONICAL BORE ANODE

When the plasma enters the pinch phase, strong electric fields are generated in and near the compressed plasma. Figure 3 shows the ion density profile and the magnitude of the electric field 25 ns into the pinch phase for the conical bore case. The plasma at minimum radius has been compressed to greater than 1000x its initial density with electric fields up to 3 MV/mm generated near the plasma-vacuum boundary. These strong electric fields accelerate ions up to 1 MeV (Figure 4a). These accelerated ions are moving preferentially away from the anode with ions moving away from the anode being 10 times more energetic than those moving towards the anode. The energetic ions generate a large amount of beam-target fusion neutrons in propagating through the compressed plasma. (Figure 4b) shows the neutron energy distribution distinguishing neutrons born with 2.5 mm of the Z-axis as "pinch neutrons". The neutrons from the pinch region comprise 80% of the total yield and have a very broad energy distribution indicative of being dominated by beam-target fusion.

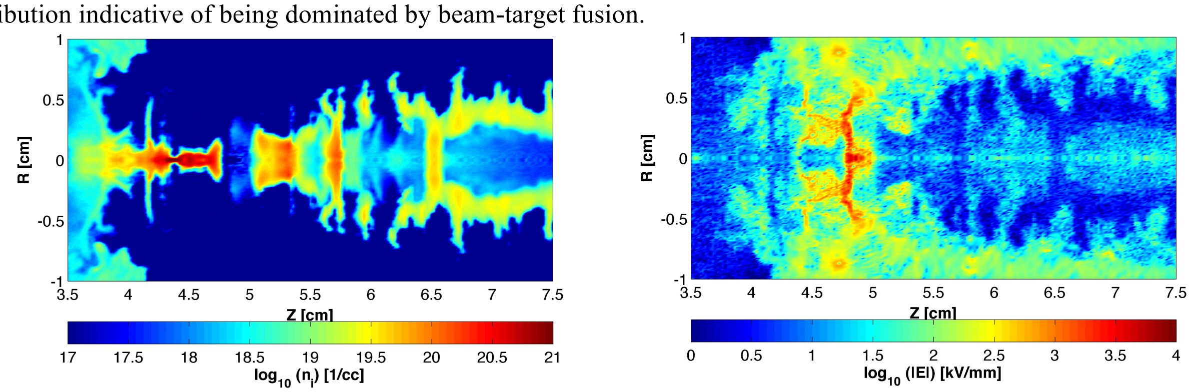

FIGURE 3 (Color Online) Ion density and Electric field for the conical bore case near time of peak neutrons, 25 ns into the pinch phase. The plasma has been compressed to greater than 1000 times the initial gas density forming a 3 cm long pinched plasma. Along the plasma vacuum interface there are electric fields up to 3 MV/mm over distances of a 1 mm while inside the compressed plasma there are fields up 30 kV/mm extending over a majority of the length of the plasma.

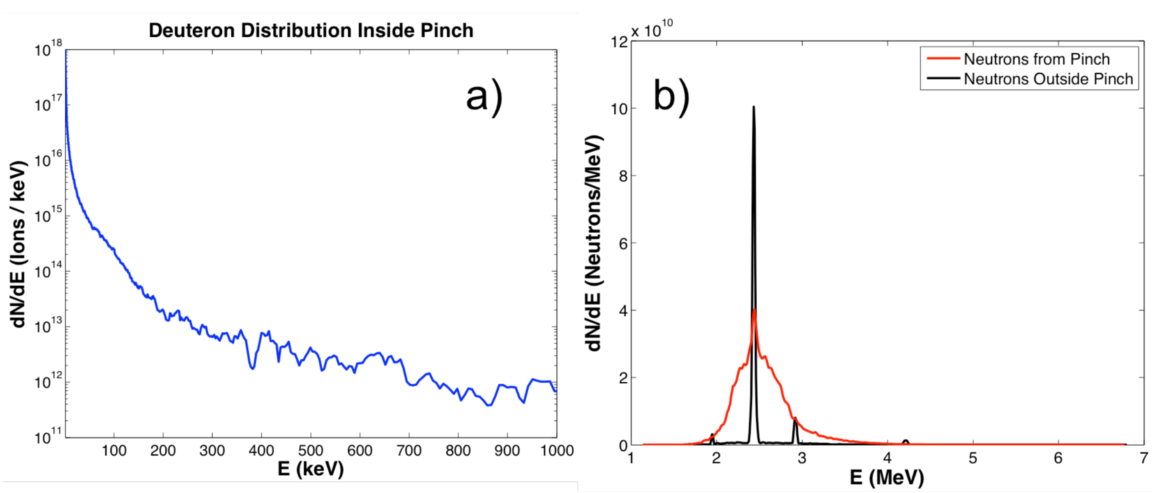

FIGURE 4 (Color Online) a) The deuteron ion energy spectrum with 2.5 mm of the z-axis at the same time as Figure 3. There is a small population of very energetic ions inside the pinch region with energies up to 1 MeV. b) The energy distribution of the all of the neutrons produced in the simulation. The neutrons emanating from within 2.5 mm of the z-axis comprise 80% of the total yield and have a broad energy distribution indicative of strong beam-target component in contrast to neutrons born outside this radius which come from ions with kinetic energies small compared to the D-D fusion energy.

COMPARISON OF ANODE SHAPE ON NEUTRON PRODUCTION

Each of the different anode configurations only varied in shape of tip, the last 10% of the total anode length. For each anode, the cathode structure, gas fill, and pulse power driver were kept the same. These preliminary results, which are still in progress, show that the conical bore shape performs the best, producing more neutrons than the conventional round anode in only half of the simulated phase phase time. In contrast, the anode which tapers to a conical point performed the worst, suffering a significant restrike near back of the anode early into the pinch phase which diverted 80% of the drive current from the anode tip and underperforms the other anode shapes by an order of magnitude. Currently only the simulation of conventional Round tip anode has completed with the neutron production having dropped to less than 5% of the peak for the last 20 ns of simulated time. The Hollow Round tip simulation is near completion currently producing neutrons at rate approximately 10% of it's peak value. The conical bore has gone nearly twice as many time-steps as conventional Round tip but the necessity of following the electron cyclotron motion has kept the time step considerably smaller and thus has limited simulated time in the pinch phase. However, even with less simulated time the conical bore tip has produced 10% more neutrons in half of the time.

Anode Shape	Total Neutron Yield	Simulated Time into Pinch Phase (ns)
Round Tip	6.4×10^{10}	80
Hollow Round Tip	5.1×10^{10}	78
45^{o} Conical Bore Tip	7.4×10^{10}	36
45^{o} Conical Tip	1.2×10^{9}	12

TABLE 1 Summary table of the total simulated time and current neutron yield for each anode shape. The Hollow Round case and Conic Hollow cases are in-progress runs.

SUMMARY

We have presented preliminary results in the development of new simulation capability to extend the prior work on fully kinetic kJ DPFs to larger devices. This new simulation capability captures pulse power driver effects, includes full run-down and run-in phases and successfully transitions from a fluid description to a fully kinetic description prior to the pinch phase. Preliminary simulations demonstrate that modification to the shape of the anode tip can improve or dramatically reduce neutron yield performance over the conventional round tip shape.

ACKNOWLEDGEMENTS

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory (LLNL) under Contract DE-AC52-07NA27344 and supported by the Laboratory Directed Research and Development Program (11-ERD-063) at LLNL. This work supported by Office of Defense Nuclear Nonproliferation Research and Development within U.S. Department of Energy's National Nuclear Security Administration. Computing support for this work came from the LLNL Institutional Computing Grand Challenge program.

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